VATTEN 66:193–198. Lund 2010

NEW APPROACHES TO SPRING FLOOD FORECASTING IN SWEDEN

by KEAN FOSTER[1], JONAS OLSSON[1] and CINTIA B. UVO[2]
1 SMHI, Folkborgsvägen 1, 601 76 Norrköping
2 Division of Water Resources Engineering, Lund University, Box 118, SE-221 00 LUND
e-mail: Kean.foster@smhi.se , Jonas.olsson@smhi.se , Cintia.Uvo@tvrl.lth.se

Abstract

Over the last two decades there has been little improvement in the accuracy of hydrological forecasts of spring floods in Sweden and hydropower accounts for nearly 47 percent of Sweden's energy production. A new research project at SMHI in collaboration with Lund University proposes to develop a multi-method system of forecasting the spring floods in an attempt to increase both the lead time and the accuracy of the forecasts. Recent advances in climate modelling and seasonal forecasting have opened up new ways to improve the spring flood forecasts. By taking advantage of these developments and building on previous works it is hoped that an improved system can be developed. The plan is to use a GCM-based multi-model system to make a first forecast early in the season followed by forecasts made by a modified HBV based system as the season progresses.

Key words – Canonical correlation analysis, CCA, downscaling, HBV, hydrological forecasts, multi-method system, spring floods

1. Introduction

Water resources and their management are more important today than ever before, be it for consumption, industry or power generation. In 2008 hydropower accounted for nearly 47 percent of Sweden's energy production (SCB 2010) and approximately 19 percent of the global energy production (SFFE 2010).

Information regarding streamflow is essential to the hydropower industry, as it allows the producers to plan operations. In cold regions, like Scandinavia, precipitation during the winter months is often stored in the catchments as snow and only later released into the watercourses when it melts. This creates a season of below average flows followed by a short period of extreme flows, and allowances must be made for this in the operations. With the help of hydrological forecasts it is possible to plan operations so that the as much of the potential production is realised while reducing the risk for reservoirs running "dry" or having to spill water. It therefore stands to reason that any improvements in the forecasts will lead to improvements in productivity.

At present most operational streamflow forecasts are made using an ensemble of representative data, generally in the form of historical observations, to run a hydrological model to generate an ensemble forecast for the spring flood. The accuracy of this method, however, has not shown much improvement over the last two decades. It is for this reason that there is work being carried out to develop a multi-method system for forecasting the spring floods.

2. Current practice at SMHI

The current system for spring flood forecasts at SMHI is based on historical meteorological observations. For the river to be forecasted, a calibrated set-up of the HBV model (Bergström, 1976; Lindström et al., 1996) is run with observed temperature and precipitation as input until the start of the forecast. This provides an optimal description of the current hydrological state. Then, an ensemble of observed time series of temperature and precipitation during the spring flood period from previous years is used as input. The output is an ensemble of discharge time series during the spring flood period.

For each series, accumulated discharge since the start of the forecast is calculated and this ensemble is expressed in terms of five percentiles: minimum, 25 %, median, 75 % and maximum. The main forecast variable, and the one considered here, is the median value of accumulated discharge, i.e. the spring flood volume.

In connection with a recent review by Arheimer et al. (2010), the accuracy of spring flood forecasts (ensemble median) in seven catchments issued since 1988 were evaluated. In terms of volume error, no clear improvement over time was found, but an overall constant spread between approximately ±50 % (Figure 1).

The absence of improvement over time is not surprising since the system is constant. The only difference between successive years is that one more historical year is added to the historical ensemble. This will gradually lead to a better description of the climatological range of variability, but has very little impact when evaluated only in terms of ensemble median spring flood volume.

Arheimer et al. (2010) further reviewed different approaches to improve performance of the spring flood forecasting system made over the years. Perfectly accurate meteorological forecasts would reduce the error by ~50 %. Reduction of the remaining error was found possible mainly by (1) up-dating of snow water equivalent at the time of the forecast and by (2) bias correction of systematic errors caused by imperfect model calibration.

3. Tests of approaches based on climate forecasts

3.1. Climate forecasts

Seasonal climate forecasts are most commonly forecast of temperature and precipitation issued monthly for a period of consecutive 3-month season up to 9 months in advance. Global models are used for this type of forecast and they can be coupled to the ocean or simply atmospheric models that are run from forecast sea surface temperature (SST) or persisted SST anomalies.

The most recent seasonal climate forecast systems make use of the multi-model methodology to provided probabilistic forecasts due to the chaotic characteristic of the atmosphere. Each global model is run from many different starting conditions that are represented by the state of the atmosphere in different days (up to 40 different days in some cases). Forecasts are provided as the probability of the average precipitation or temperature for three consecutive months to be above, below or near normal (three equiprobable categories with respect to the 30-year average) up to nine months in advance. The reader is referred to Barnston et al. (2003), Saha et al. (2006), ECMWF (2010) for further detailed description of diverse seasonal forecast systems.

3.2. Input ensemble adjustment by consolidated seasonal forecasts

In a recent research project at SMHI, a system for so-called Consolidated Seasonal Forecasts (CSF) was developed. In this system, several models representing different approaches to seasonal forecasting (e.g. ECMWF dynamical model and different statistical models) were used to generate weighted forecasts. The weighting was done to reflect the accuracy of each model with respect to season and lead time. The output from the system is in the form of 3-monthly temperature and precipitation anomalies from a reference climate specified by the NCEP/NCAR reanalysis (Kalnay et al., 1996).

The CSF system was evaluated with respect to spring flood forecasting. The approach used was to adjust the historical ensemble of temperature and precipitation time series in line with the forecasted anomalies. For

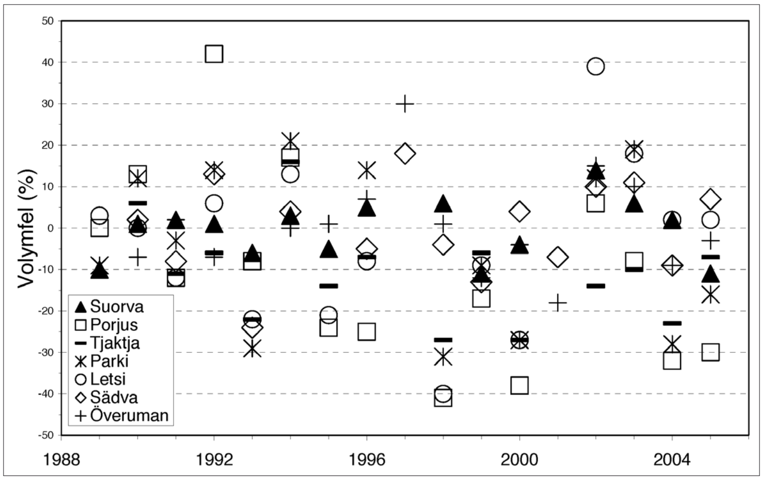

Figure 1. *Volume errors in the spring flood forecasts for seven rivers between 1989 and 2005.*

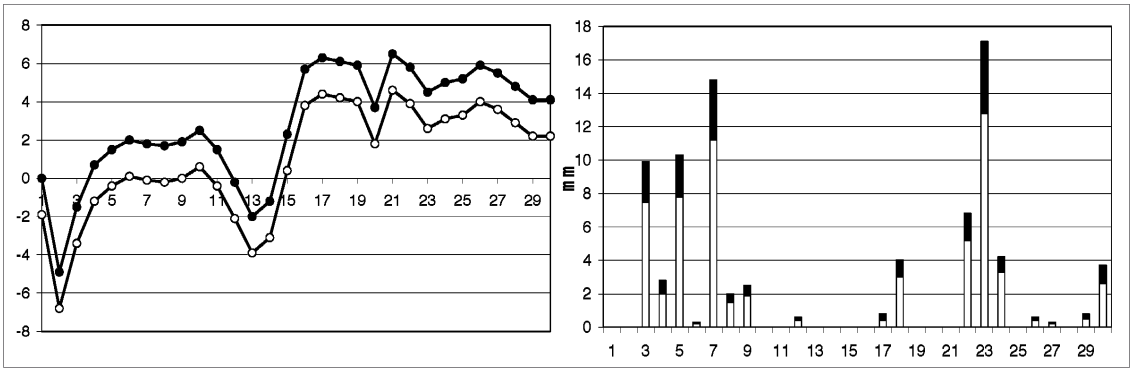

Figure 2. *(Left) Original (white dots) and adjusted (black dots) temperature reflecting a forecasted monthly anomaly of +1.5°C. (Right) Original (white) and adjusted (white+black) precipitation reflecting a forecasted monthly anomaly of +30%.*

temperatures the adjustment was additive and for precipitation it was multiplicative (Figure 2). The adjusted series were then used to generate spring flood forecasts by the HBV model as outlined above.

The approach was tested in sub-catchments of three large rivers in northern Sweden: Boden (Luleälven), Volgsjön (Ångermanälven) and Svegsjön (Ljusnan). The HBV model was set up and calibrated using 20–30 years of historical observations prior to 1992. Then hindcasts were made for each spring flood in the period 1992–2004 using three types of input ensembles.

- ORG: Original unadjusted historical time series of temperature and precipitation.
- PEF: Perfect forecasts. These were produced by adjusting the input ensemble by the actually observed monthly anomalies.
- CSF: Input ensemble adjusted according to the CSF system output.

The accuracy of the hindcasts were evaluated in terms of the Mean Absolute Error (MAE) of the forecasted spring flood volume.

The results indicate that the forecast error can be approximately halved if the forecasted monthly anomalies are exactly correct (Table 1), which is in line with previous investigations (e.g. Arheimer et al., 2010). The remaining error is related to HBV model uncertainty. The CSF forecast error is however slightly higher than the error obtained using the original, unadjusted input ensemble (Table 1).

That the CSF forecasts were less accurate than the original forecasts was found to be related to large differences between the CSF reference climate (i.e. the NCEP/NCAR reanalysis) and the actual observations in the test catchments. Because of these differences, even if a forecasted anomaly was well in line with the anomaly in the reference climate it was often very different from the actually observed anomaly. Even with respect to the reference climate the skill of the CSF anomalies were limited, and these differences in climatology of course decreased the skill even further. The final skill of the forecasted precipitation anomalies was not sufficient for any improved forecasts. Some useful skill was however found in the forecasted temperature anomalies. A preliminary test indicated that by combining CSF-adjusted historical temperatures with unadjusted historical precipitation a slightly lower MAE than in the original forecasts (ORG) could be attained.

3.3. GCM-based statistical forecasting of spring flood volume

Recent work carried out by Foster and Uvo (2010) has shown that, by using statistical methods to downscale general circulation model (GCM) forecast fields, it is possible to estimate the volume of spring floods up to five months in advance. The method uses a canonical correlation analysis (CCA) to identify predictors from one or more GCMs, such as temperature and wind direction, which have the best correlation with the

Table 1. *Average MAE of spring flood forecasts in the period 1992–2005.*

Catchment	Boden			Volgsjön			Svegsjön		
Forecast type	ORG	PEF	CSF	ORG	PEF	CSF	ORG	PEF	CSF
MAE (%)	10.4	4.4	13.4	26.8	13.0	30.9	25.0	10.9	28.2

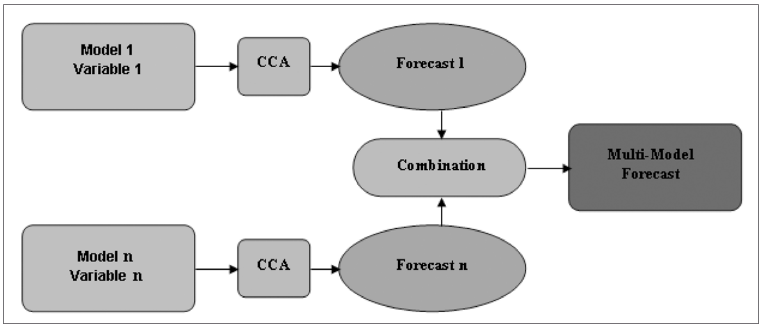

Figure 3. *Schematic diagram of the multi-model forecast system, starting with a GCM-forecast variable then deriving the model formula, with the help of a canonical correlation analysis (CCA), which is used to make a forecast that is combined with other forecasts to give the multi-model forecast.*

spring flood volume and derives a model formula. A combination of these individual models is then combined to create a multi-model; figure 3 shows a schematic diagram of the methodology.

The multi-model system was tested in selected unregulated catchments in Norway and showed skill at forecasting the spring flood volume five months in advance. Figure 4 shows the location of the gauging stations and the multi-model cross-validated R^2 values for eleven of the catchments tested. The multi-model performed best in catchments that are located near the coast or on the western slopes of the Scandinavian Mountains. This is expected as these stations are exposed to the prevailing winds from the Atlantic Ocean and North Sea, which are a major moisture source for the region, and two of the GCM predictors used in the study are components of these winds i.e. meridional wind velocity and zonal wind stress.

The noticeable difference in model performance for two of the stations, Risefoss (Ris) and Eggafoss (Egg), can be explained by the fact that they are not as exposed to the prevailing winds as the others and it is concluded that the predictors used in the study were not optimal for these two stations. This highlights the need to understand the climatic relationships that affect the hydrology in the region of interest so that the appropriate GCM predictors can be better identified.

4. Development of a multi-method system

The aim of ongoing research, at SMHI in collaboration with the Department of Water Resources Enginnering at Lund University, is to develop a multi-method approach to spring flood forecasting. The idea is to use a combination of methods to forecast the spring floods. By doing this it is hoped that it will be possible to issue a first forecast earlier in the season and improve the accuracy of the forecasts in general. It is proposed that the GCM-based multi-model be used to make the first forecasts and as the season progresses to switch to a system that uses HBV, or perhaps another hydrological model, to make the forecasts.

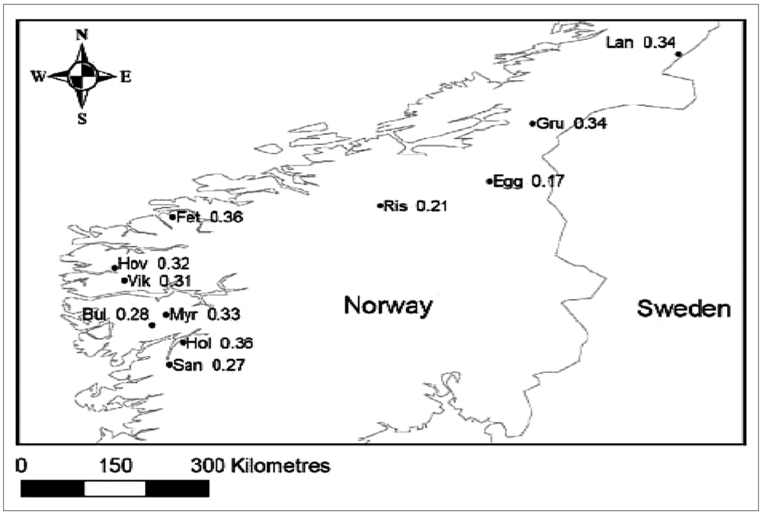

Figure 4. *Map showing the location of the gauging stations and the R2 values for multi-model cross-validated forecasts made for the stations (Foster and Uvo 2010).*

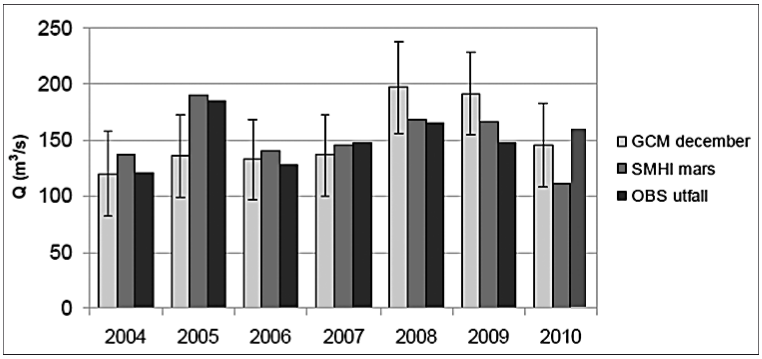

Figure 5. *Comparison of the forecasted and observed average flow rates for the spring floods at Öster Noren in Jämtland.*

A preliminary test compared forecasts made by the GCM-based multi-model and the present day HBV-based system with observations (Figure 5). The results show that the GCM-based multi-model has similar performances to the HBV-based system and suggest that the there is merit to using it to make forecasts early in the season.

The strategy from here is two pronged; the first is to identify which GCMs and variables to use in the GCM-based multi-model, and the second is to improve the accuracy of the HBV based system. Identifying which GCMs and variables to use will require a better understanding of the climatic relationships that affect the hydrology in the regions of interest so that the correct predictors can be chosen. To improve the accuracy of the HBV-based system it requires better temperature and precipitation data, two possible ways to achieve this are to either use forecast temperature and precipitation data from sources like the European Centre for Medium-Range Weather Forecast (ECMWF) or to select so called analogue years from the historical data sets that best match the year in question. Both of these methods need to be tried and tested against each other to determine which is most suitable.

The hope is to develop a system that will issue a spring flood forecast in December followed by at least one more forecast nearer the spring flood.

5. Concluding remarks

Several attempts to improve performance of SMHIs current spring flood forecasting system have been made over the years (see Arheimer et al., 2010), but any significant improvement has proved difficult to reach. This indicates that today's forecasts already are of a high quality. However, by the recent advances in climate modelling and seasonal forecasting, new ways to improve the spring flood forecasts open up. Initial attempts to apply these new tools in this context have shown mixed results (sections 3.2–3.3), but a lot of knowledge and experience have been gained which will be important in the ongoing development. We do believe that the strategies suggested have the potential to generate an improved system for spring flood forecasting.

The task of developing a multi-method forecast system will thus be a challenging one. Sweden is a long country that stretches over 1500 km from north to south, which means that the climate varies from region to region making identifying the required GCM forecast variables difficult and time consuming. The GCM-based multi-method relies on being able to connect GCM forecast variables to the spring flood volumes, but for some catchments the link between them can be rather tenuous which means that forecasts can't be made as long in advance as required.

To be able to select analogue years from the historical data sets will require developing a method of comparing the different years. One of the ways to compare the different years is to try to match circulation patterns that occur in the forecast year with those from the historical years. Although this is possible, developing a method to analyse many numerous years quickly will pose a challenge.

Acknowledgements

We gratefully acknowledge funding from Elforsk/HUVA, through research project *A multi-method system for spring flood forecasts*, the Swedish Research Council Formas, through research project *Hydroimpacts 2.0*, and the Swedish Meteorological and Hydrological Institute (SMHI). The study was partly performed within COST Action 731, *Propagation of uncertainty in advanced meteo-hydrological forecast systems.*

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